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Calophyllum inophyllum L. – A prospective non-edible biodiesel feedstock. Study of biodiesel production, properties, fatty acid composition, blending and engine performance

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ABSTRACT

Recently, non-edible oil resources are gaining worldwide attention because they can be found easily in many parts of the world especially wastelands that are not appropriate for cultivating food crops, eliminate competition for food, more efficient, more environmentally friendly, produce useful by-products and they are more economical compared to edible oils. *Jatropha curcas, Pongamia pinnata, Calophyllum inophyllum, Croton megalocarpus* and *Azadirachta indica* are some of the major non-edible feedstocks for biodiesel production. This paper investigates the potential of *Calophyllum inophyllum* as a promising feedstock for biodiesel production. In this paper, several aspects such as physical and chemical properties of crude *Calophyllum inophyllum* oil and methyl ester, fatty acid composition, blending and engine performance and emissions of *Calophyllum inophyllum* methyl ester were studied. Overall, *Calophyllum inophyllum* appears to be an acceptable feedstock for future biodiesel production.

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1. Introduction

The global awareness of energy crisis and the environmental impacts linked with fossil fuels has led to examine the prospect of using alternative energy resources such as biodiesel. Biodiesel is defined as the mono-alkyl esters of long chain fatty acids (FAME) derived from renewable lipids such as vegetable oils and animal fats and alcohol [1–5]. Biodiesel is renewable, biodegradable, non-toxic, portable and readily available, possesses inherent lubricity, a higher flash point and cetane ignition rating, and contributes to more reduction in emissions compared to diesel. All these parameters make it an ideal fuel for the future [6].

One of the most significant factors that promote the production of biodiesel worldwide is the wide range of available feedstocks [7,8]. Globally, there are more than 350 crops identified as potential feedstock for biodiesel industry [9,10]. It was found that feedstock alone represents 75% of the overall biodiesel production cost. Therefore, selecting the cheapest feedstock is vital to guarantee the low production cost of biodiesel [1,10–13].

Edible oils such as soybeans and palm oil are considered as the first generation of biodiesel feedstock. However, their use has raised many concerns such as the food versus fuel crisis and major environmental problems such as serious destruction of vital soil resources, deforestation and usage of much of the available arable land. Moreover, in the last 10 years the prices of vegetable oil plants have increased dramatically [10,14–16].

1.1. Why non-edible oils?

Non-edible oils are gaining worldwide attention because they can be found in many parts of the world. Moreover, they can eliminate competition for food, more efficient, more environmentally friendly, produce useful by-products and they are more economical compared to edible oils. Non-edible oils are regarded as a second generation biodiesel feedstocks. Some of the non-edible oils are *Jatropha curcas* L., *Milo (Thespesia populnea* L.*)*, *Pongamia pinnata (Karanja)*, *Moringa oleifera*, *Calophyllum inophyllum*, *Croton megalocarpus*, Castor oil (*Ricinus communis* L.), Neem (*Azadirachta indica)*, *Cerbera odllam* (sea mango), *Sapium sebiferum* L., *Yellow oleander (Thevetia peruviana Schum.)*, *Madhuca indica* (Mahua) and *Madhuca longifolia*, silk cotton tree (*Ceiba pentandra*), *Hevea brasiliensis* (Rubber) and *Eruca Sativa* Gars. However, most of these non-edible oils have high free fatty acid (FFA) values. Therefore, transesterification with alkali based catalyst yields a considerable amount of soap. Soaps are emulsifiers that make the separation of glycerol and ester phases more difficult. Further, the catalyst that has been converted to soap is no longer available to accelerate the biodiesel forming reaction. Therefore high catalyst loading is required. Acid catalyzed transesterification was found to be a good solution to this problem. However the reaction rate was considerably less, requiring lengthy reaction periods. Therefore, it has been well established in the literature that the best approach to produce biodiesel from non-edible oils with high FFA values is the acid esterification followed by the alkaline transesterification process (acid–base catalyzed transesterification). Many recent publications have reported on the possibility of biodiesel production from non-edible oils such as Refs. [2,5,10,17–36]

1.2. Objectives of this paper

The main objective of the present paper is to examine the opportunity of biodiesel production from *Calophyllum inophyllum* as a potential source for future energy supply. Several related aspects such as physical and chemical properties of crude *Calophyllum inophyllum* oil (CCIO) and methyl ester (CIME), fatty acid composition (FAC), biodiesel–diesel blending, biodiesel–biodiesel blending, crude oil–diesel blending and engine performance of *Calophyllum inophyllum* methyl ester (CIME) were covered in this paper. A comparison with existing literature such as [13,23,24,30,37–40] was also well covered and presented. In fact there are no any published papers that review the potential of *Calophyllum inophyllum* oil as a prospective source for biodiesel production. In view of this, this article offers an in-depth understanding of *Calophyllum inophyllum* as promising feedstock for biodiesel production.

2. Advantages of *Calophyllum inophyllum*

There are many advantages of using *Calophyllum inophyllum* L. some of these advantages are as follows [38,41]:

- *Calophyllum inophyllum* has high survival potency in nature, still productive up to 50 years.
- It does not compete with food crops.
- Its trees serve as windbreaker at the seashore where it can reduce abrasion, protect crops and provide ecotourism and conservation of coastal demarcation.
- It has higher oil yield than *Jatropha curcas* (Table 2).
- It has high heating value.
- Its biodiesel meets the US ASTM D6751 and European Union EN 14214 biodiesel standards.
- Its biodiesel can be used as a potential substitute for diesel as other plant/seed feedstocks have been used or proposed to be used.
- Its biodiesel is compatible with diesel and possesses better lubrication capability.

3. Botanical description and of distribution of *Calophyllum inophyllum*

Calophyllum inophyllum is a multipurpose tree belonging to the family *Clusiaceae*, commonly known as mangosteen family. This plant has multiple origins including East Africa, India, South East Asia, Australia, and the South Pacific. *Calophyllum inophyllum* is known by various names around the world [40,42–45]. Table 1 shows different vernacular names of *Calophyllum inophyllum* in

Nomenclature

ASTM	American Society for Testing and Materials
ASTM D6751	ASTM biodiesel specification
CCIO	crude *Calophyllum inophyllum* oil
CIME	*Calophyllum inophyllum* methyl ester
CME	canola methyl ester
CMME	*Croton megalocarpus* methyl ester
COME	coconut methyl ester
CFPP	cold filter plugging point
CO	carbon monoxide
CP	cloud point
EN	European standards
EN 14214	EN biodiesel specification
FP	flash point
HC	hydrocarbon
JB	jatropha biodiesel
KB	karanja biodiesel
NO	nitric oxide
NO_x	mono-nitrogen oxides
PB	polanga (*Calophyllum inophyllum*) biodiesel

some selected countries of the world [46]. Fig. 1 shows the distribution map of *Calophyllum inophyllum* around the world [47]. As can be seen this tree is widely available in India, South East Asia and Australia. It grows in areas with an annual rain of 1000–5000 mm at altitudes from 0 to 200 m. *Calophyllum inophyllum* is a low-branching and slow-growing tree with two distinct flowering periods of late spring and late autumn. But sometimes its flowering may occur throughout the year. *Calophyllum inophyllum* grows best in sandy, well drained soils. However it tolerates clays, calcareous, and rocky soils. The tree supports a dense canopy of glossy, elliptical, shiny and tough leaves, fragrant white flowers, and large round nuts. Its size typically ranges between 8 and 20 m (25–65 ft) tall at maturity, sometimes reaching up to 35 m (115 ft). The growth rate of the tree is 1 m (3.3 ft) in height per year on good sites. Its leaves are heavy and glossy, 10–20 cm (4–8 in.) long and 6–9 cm (2.4–3.6 in.) wide, light green when young and dark green when older. Fruits are spherical drupes and arranged in clusters. The fruit is reported to be pinkish-green at first; however, it turns later to be bright green and when ripe, it turns dark grey-brown and wrinkled. The tree yield is 100–200 fruits/kg. In each fruit, one large brown seed 2–4 cm (0.8–1.6 in.) in diameter is found. The trees yield 3000–10,000 seeds/tree/season. The seed is surrounded by a shell and a thin layer of pulp of 3–5 mm. *Calophyllum inophyllum* oil is non-edible and dark green. Traditionally, its oil has been used as a medicine, soap, lamp oil, hair grease and cosmetic in different parts of the world. Recently, *Calophyllum inophyllum* has been proposed as a source of biodiesel [2,29,30,40,45,48–52]. Fig. 2 shows *Calophyllum inophyllum* tree and fruit.

Table 1
Different vernacular (Dialectal) names of *Calophyllum inophyllum* around the world [46].

Country	Vernacular (Dialectal) name
Bangladesh	Punnang
Cambodia	Kchyong, Khtung
India	Poon, Polanga, Undi, Sultan champa
Indonesia	Bintangur, Nyamplung
Malaysia	Bintangor, Penanglaut
Thailand	Naowakan, Krathing, Saraphee
Philippines	Bitaog, Butalau,Palomaria
Guam	Da′ok, Da′og
Tahiti	Tamanu

4. Preparation and extraction of *Calophyllum inophyllum* oil

After collection of *Calophyllum inophyllum* fruit, the seeds were dried under sunlight for 2–3 days. It was found that, the yield of the seeds after drying was 100–150 seeds/kg and the water content inside the seeds was 9–10% when the seeds were heated at 105 °C for 24 h and the ash content was 40.31% when heated at 700 °C for minimum 4 h. The kernel was then separated from the shell and found to have high oil content (70%). The ideal conditions to preserve the kernel were 26–27 °C and 60–70% humidity. The place in which the kernel was stored was well ventilated and the storing period was not too long. Fig. 3 shows *Calophyllum inophyllum* fresh fruit, seed before and after peeling process, seeds' shell and kernel and dried kernel [53].

Before extraction, the kernels were mixed with rice husk. This is very important to increase the oil yield during the extraction process. There are two types of pressing machine that used to extract the oil from the kernel: hydraulic manual pressing machine and screw extruder machine. The oil extracted using pressing machine was very little and about 20–30%. Therefore, hydraulic machine was used to increase the oil yield from *Calophyllum inophyllum*. The remained cake after extraction has a high commercial and marketing value as a by-product. Fig. 4 shows the kernel before extraction, seeds cake and the resulted extracted oil which was reported to be dark green [53].

Table 2
Oil content of some potential feedstock for biodiesel [29,32,54,58,59].

Feedstock	Source	Oil wt% dry	Oil yield (kg/ha/year)
Nyamplung (*Calophyllum inophyllum*)	Seed kernel	40–73/60–64	4680
Palm oil (*Elais guineensis*)	Pulp+Kernel	45–70+46–54	4000–6000
Coconut (*Cocos nucifera*)	Kernel	60–70	–
Physic nut (*Jatropha curcas*)	Seed kernel	40–60	1900–2500
Pongam (*Pongamia pinnata*)	Seed	27–39	225–2250
Rubber seed (*Hevea brasiliensis*)	Seed	40–50	40–50
Kelor (*Moringa oleifera*)	Seed	30–49	–
Euphorbia lathyris L.	Seed	48	1500–2500
Castor (*Ricinus communis*)	Seed	43–45	500-100
Sunflower (*Helianthus annus*)	Seed	38–48	500–1500
Soybean	Seed	17	200–600
Colza (*Brassica campestris*)	Seed	40–48	500–900

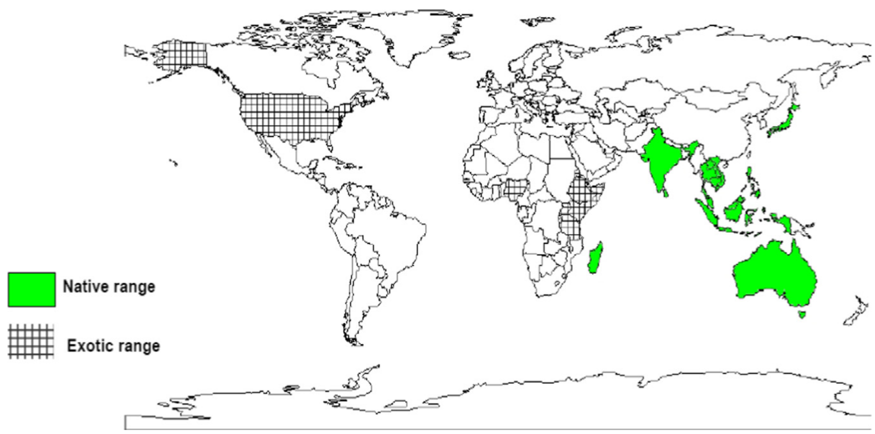

Fig. 1. Distribution map of *Calophyllum inophyllum* around the world.

Fig. 2. *Calophyllum inophyllum* tree and fruits.

5. Yield and characterization of *Calophyllum inophyllum* oil

The yield of *Calophyllum inophyllum* oil per unit land area was reported to be higher than 4 t/ha. The oil is tinted green, thick, and nutty smelling. The oil content of *Calophyllum inophyllum* seed kernel is in the range of 40–73% [2,21,50,54–57]. Table 2 shows the oil content of *Calophyllum inophyllum* besides some other potential feedstocks for biodiesel [29,32,54,58,59]. *Calophyllum inophyllum* yields about twice as much oil per hectare as *Jatropha curcas* [60,61]. Hathurusingha et al. [56] reported that the oil content of *Calophyllum inophyllum* fruits seems to increase with maturity. Crude *Calophyllum inophyllum* oil was reported to be highly viscous (71.98 mm^2/s, 59.17 mm^2/s and 55.677 mm^2/s) at 40 °C and acidic (44 mg KOH/g, 59.33 mg KOH/g and 41.74 mg KOH/g) [37,44,62]. However, Belagur and Chitimi [63] reported that the acid value of honne oil (*Calophyllum inophyllum*) is only 4.76 mg KOH/g. Moreover, a comparison with other non-edible feedstocks revealed that *Calophyllum inophyllum* had an extremely high acid value compared to *Jatropha curcas* acidic (17.63 mg KOH/g), *Croton megalocarpus* (12.07 mg KOH/g) and *Moringa oleifera* (8.62 mg KOH/g) respectively [44]. The crude *Calophyllum* oil is dominated by triacylglycerol (76.7%) followed by diacylglycerol (7%) and free fatty acids (5.1%) [51,62].

Tables 3 and 4 conduct a comparison of physical and chemical properties between *Calophyllum inophyllum* oil and other edible and non-edible vegetable oils taken from the literature. It can be seen that *Calophyllum inophyllum* oil has the highest viscosity, flash point and acid value compared to other non-edible oil.

6. Fatty acid composition (FAC) of *Calophyllum inophyllum*

The fatty acid composition is an important property for any biodiesel feedstock. The percentage and type of fatty acids

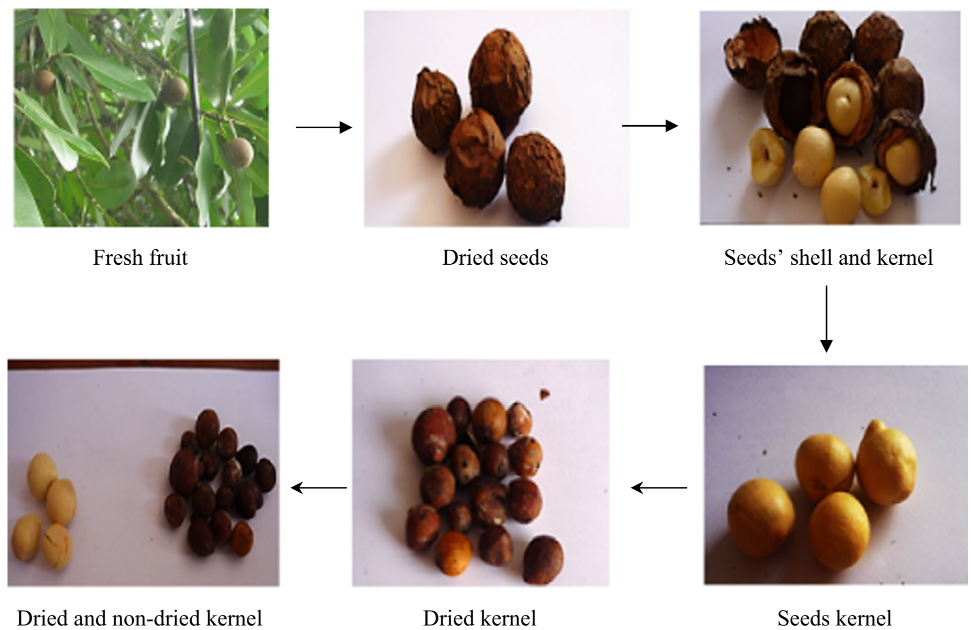

Fig. 3. *Calophyllum inophyllum* fresh fruit, dried fruit, seed before and after peeling.

Fig. 4. Kernels before extraction, seeds cake and the resulted extracted oil.

composition of *Calophyllum inophyllum* L. oil varies depending on the quality of the feedstock, growth conditions and the geographical location in which the plant has grown. The main fatty acids in *Calophyllum inophyllum* L. were tabulated in Table 5. It can be seen that (CCIO) is mainly dominated by C18:1 followed by C18:2, C18:0 and C16:0. These results were also in agreement with the results found in the literature [7,20,29,37,53,62–66]. Moreover, a comparison of fatty acid

Table 3
Physicochemical properties of *Calophyllum inophyllum* oil and other edible and non-edible vegetable oils [37,39,55,58,59].

Oil	Specific gravity	Viscosity (cSt) at 40 °C	Cetane number	Flash point (°C)	Acid value (mg KOH/g)	Calorific value (MJ/kg)
Calophyllum inophyllum	0.896	71.98	–	221	44	39.25
Rubber	0.91	66.2	37	198	34	37.5
Cotton	0.912	50	41.2–59.5	210	0.11	39.6
Pongamia pinnata	0.913	27.84	45–67	205	5.06	34.0
Jatropha curcas	0.920	18.2	33.7–51	174	3.8	38.5
Neem	0.912–0.965	20.5–48.2	51	34–285	–	33.7–39.5
Castor (*Ricinus communis*)	–	297[a]	–	260	–	39.500
Sunflower (*Helianthus annus*)		37.1[a]	37.1	274	-	39.575
Soybean		32.6[a]	37.9	254	–	39.623
Colza (*Brassica campestris*)		37[a]	37.6	246	–	39.709

[a] At 37.8 °C.

Table 4
Physical and chemical properties of (CCIO).

	Property	Atabani et al. [44]	Belagur and Chitimi [63]	Rizwanul Fattah et al. [66]
1	Kinematic viscosity (mm²/s) at 40 °C	55.677	32.48 ± 2	53.136
2	Kinematic viscosity (mm²/s) at 100 °C	9.5608	N/D	N/D
3	Dynamic viscosity (mPa s) at 40 °C	51.311	N/D	48.973
4	Viscosity index (VI)	165.4	N/D	159.2
5	Flash point (°C)	236.5	235 ± 2	218.5
6	CFPP (°C)	26	N/D	27
7	Cloud Point (°C)	N/D	-2.5 ± 1	8
8	Pout point (°C)	N/D	-08 ± 1	8
9	Cetane number	N/D	51–56	N/D
10	Density (g/cm³) at 15 °C	0.951	0.910 ± 3	N/d
11	Specific gravity at 15 °C	0.952	N/D	N/D
12	Acid value (mg KOH/ g oil)	41.74	4.76	40
13	Caloric value (kJ/kg)	38,511	39,110	N/D
14	Copper strip corrosion (3 h at 50 °C)	1a	N/D	N/D
15	Cetane number	N/D	51–56	N/D
16	Saponification number	N/D	91–202	N/D
17	Iodine value	N/D	82–98	N/D
18	Refractive Index (RI) at WL 656.1	1.4784	N/D	N/D
19	Transmission (%) at WL 656.1	34.7	N/D	N/D
20	Absorbance (Abs) at WL 656.1	0.46	N/D	N/D
21	Oxidation stability (h at 110 °C)	0.23	N/D	3.28
22	PH at 26 °C	4.60	N/D	N/D

N/D ≡ Not determined

composition of *Calophyllum inophyllum* and other non-edible oils is shown in Fig. 5.

It is well known that biodiesel containing high level of unsaturation (such as polyunsaturated and monosaturated fatty acid methyl esters) is prone to autoxidation. Moreover, oxidation degradation has a negative impact on acid value and kinematic viscosity. In contrast to that, biodiesel containing high amount of unsaturated fatty acids has good flow properties compared to saturated fatty acids. Poor cold flow properties generally limit the application of biodiesel in cold countries.

7. Biodiesel production from *Calophyllum inophyllum* oil

The acid value of vegetable oil is defined as the number of milligrams of potassium hydroxide required to neutralize the free acid present in 1 g of the oil sample [10,39,44,52]. From literature, it was found that the acid values of crude *Calophyllum inophyllum* oil were 41.74 mg KOH/g oil [53], 44 mg KOH/g oil [39], 39.8 mg KOH/g oil [40], 44 mg KOH/g oil [37] and 40 mg KOH/g oil [66] respectively. The transesterification procedure cannot be successful when the acid value is more than 4 mg KOH/g oil. Therefore, to produce biodiesel, the FFA must be converted to esters using acid catalytic esterification before attempting alkaline catalytic esterification [10,40,52].

Table 6 shows a summary of biodiesel production from *Calophyllum inophyllum* oil [13,37,39,66].

According to [13,53], production of biodiesel from crude *Calophyllum inophyllum* oil was suggested to be as follows:

1) Pre-treatment process; (2) Esterification process (2 times); (3) Transesterification process; (4) Post-treatment process.
   Sahoo and Das [39] suggested the following steps:
2) Zero-catalyzed transesterification; (2) Acid-catalyzed transesterification; (3) Alkaline-catalyzed transesterification.
   While Rizwanul Fattah et al. [66] suggested the following steps:
3) Pre-treatment process (acid catalyzed esterification); (2) Alkali catalyzed transesterification process; (3) Post-treatment process.

The following section gives an example of biodiesel production from *Calophyllum inophyllum* obtained from Refs. [13,53].

7.1. Pre-treatment process

In this process, crude *Calophyllum inophyllum* oil (CCIO) was entered in a rotary evaporator and heated to remove moisture for 1 h at 95 °C under vacuum.

7.2. Esterification process

The esterification process is used when the free fatty acid (FFA) content of the refined oil is greater than 2%. According to the results presented in Table 7, the acid value of the crude *Calophyllum inophyllum* oil was measured to be 41.74 mg KOH/g oil. Therefore, a two-step acid–base catalyzed transesterification was adopted to convert crude *Calophyllum inophyllum* oil (CCIO) into *Calophyllum inophyllum* methyl ester (CIME). In this process, 50% (v/v oil) (12:1 M ratio) of methanol to refined oil and 1% (v/v oil) of sulfuric acid (H_2SO_4) were added to the pre-heated oil at 60 °C for 3 h and 400 rpm stirring speed in a glass reactor. On completion of this reaction, the products were poured into a separating funnel to separate the excess alcohol, sulfuric acid and impurities presented in the upper layer. The lower layer was separated and entered into a rotary evaporator and heated at 95 °C under vacuum conditions for 1 h to remove methanol and water from the esterified oil. This process reduced the acid value to around 11 mg KOH/g oil.

This process was repeated again using the same methodology to reduce the acid value of the oil from 11 to less than 4 mg KOH/g oil.

Table 5
Fatty acid compositions (%) of *Calophyllum inophyllum* oil.

Fatty acid	Systematic name	Formula	Structure	wt% [a]	wt% [b]	wt% [c]	wt% [d]	wt% [d]	wt% [f]
Myristic	Tetradecanoic	$C_{14}H_{28}O_2$	$C_{14:0}$	N/D	0.09	N/D	N/D	N/D	N/D
Palmitic	Hexadecanoic	$C_{16}H_{32}O_2$	$C_{16:0}$	14.7	14.6	12.01	17.9	14.8–18.5	13.9
Palmitoleic	cis-9-Hexadecenoic	$C_{16}H_{30}O_2$	$C_{16:1}$	0.3	N/D	N/D	2.5	N/D	0.2
Margraic	Heptadecanoic	$C_{17}H_{34}O_2$	$C_{17:0}$	N/D	N/D	N/D	N/D	N/D	N/D
Stearic	Octadecanoic	$C_{18}H_{36}O_2$	$C_{18:0}$	13.2	19.96	12.95	8.5	6.1–9.2	15.1
Oleic	cis-9-octadecenoic	$C_{18}H_{34}O_2$	$C_{18:1}$	46.1	37.57	34.09	42.7	36.2–53.1	40.3
Linoleic	cis-9, cis-12-octadecadienoic	$C_{18}H_{32}O_2$	$C_{18:2}$	24.7	26.33	38.26	13.7	15.8–28.5	25.6
Linolenic	cis-9-cis-12 Octadecatrienoic	$C_{18}H_{30}O_2$	$C_{18:3}$	0.2	0.27	0.3	2.1	N/D	0.2
Arachidic	Eicosanoic	$C_{20}H_{40}O_2$	$C_{20:0}$	0.8	N/D	N/D	N/D	N/D	N/D
Eicosenoic	cis-11-Eicosenoic acid	$C_{20}H_{38}O_2$	$C_{20:1}$	N/D	N/D	N/D	N/D	N/D	N/D
Behenic	Docosanoic	$C_{22}H_{44}O_2$	$C_{22:0}$	N/D	N/D	N/D	N/D	N/D	N/D
Erucic	Docosenoic (cis-13)	$C_{22}H_{42}O_2$	$C_{22:1}$	N/D	N/D	N/D	N/D	3.3	N/D
Lignocerate	Tetracosanoic	$C_{24}H_{48}O_2$	$C_{24:0}$	N/D	N/D	N/D	2.6	N/D	N/D

N/D ≡ Not detected.
*Note: Carbon number with 'zero' double bonds are saturated fatty acids, with 'one' double bonds are monosaturated and with 'two' and 'three' double bonds are polyunsaturated fatty acids.
[a] [53].
[b] [41].
[c] [37,39].
[d] [40].
[f] [66].

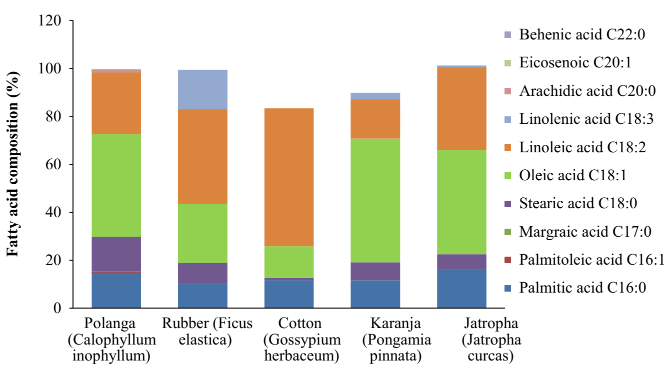

Fig. 5. Comparison of fatty acid composition of *Calophyllum inophyllum* and other non-edible vegetable oils.

The lower layer was separated and entered into a rotary evaporator and heated at 95 °C under vacuum conditions for 1 h to remove methanol and water from the esterified oil. In this reaction, FFA was converted to methyl ester and water was formed as a by-product.

7.3. Transesterification process

In this process, the esterified *Calophyllum inophyllum* oil from the previous step was reacted with 25% (v/v oil) of methanol and 1% (m/m oil) of alkaline catalyst potassium hydroxide (KOH) and maintained at 60 °C for 2 h and 400 rpm stirring speed. In this process, triglyceride was converted to methyl ester and glycerol was formed as a by-product. After completion of the reaction, the produced biodiesel was deposited in a separation funnel for 12 h to separate the glycerol from biodiesel. The lower layer containing impurities and glycerol was drawn off.

7.4. Post-treatment process

Methyl ester formed in the upper layer from the previous process was washed to remove the entrained impurities and glycerol. In this process, 50% (v/v oil) of distilled water at 60 °C was sprayed over the surface of the ester and stirred gently. This process was repeated several times until the pH of the distilled water became neutral. The lower layer was discarded and upper layer was entered into a flask and dried using Na_2SO_4 and then further dried using rotary evaporator to make sure that biodiesel is free from methanol and water.

8. Properties and qualities of *Calophyllum inophyllum* methyl ester (CIME)

The results of physicochemical properties of (CIME) were tabulated in Table 7. The following section will discuss some of these results.

8.1. Kinematic viscosity

Kinematic viscosity is the most important property of biodiesel since it affects the operation of fuel injection equipment, particularly at low temperatures when an increase in viscosity affects the fluidity of the fuel. The kinematic viscosity in biodiesel is determined using ASTM D445 (1.9–6.0 $mm^2\,s^{-1}$). According to [13], the kinematic viscosity of CIME was 5.5377 $mm^2\,s^{-1}$ compared to 5.724 $mm^2\,s^{-1}$ of [38], 5.6 $mm^2\,s^{-1}$ of [40], 4.92 $mm^2\,s^{-1}$ of [37], 4 $mm^2\,s^{-1}$ of [30] and 4.7128 $mm^2\,s^{-1}$ of [66]. All these results are in agreement with ASTM D445 and indicate that CIME is in accordance with ASTM D6751 standard specified for kinematic viscosity.

8.2. Flash point (FP)

Flash point of a fuel is the temperature at which it will ignite when exposed to a flame or a spark. Flash point varies inversely with the fuel's volatility. Flash point is measured according to ASTM D93. It was found that the FP of CIME was 168.5 °C [13] compared to 140 °C of [37], 151 °C of [38], 140 °C of [30], 146 °C of [40] and 141.5 °C of [66] respectively. These results are in agreement with ASTM D93, which requires that FP to be minimum 93 °C.

8.3. Cold filter plugging point (CFPP)

Cold filter plugging point (CFPP) is as used indicator of low temperature operability of fuels. This property has been a technical reason impairing the widespread use of this biodiesel. The CFFP tested is measured by ASTM D 6371. From Table 7 it can be seen that

Table 6
Parameters for biodiesel production from *Calophyllum inophyllum*.

Catalyst	Catalyst concentration	Alcohol	Temperature	Stirring speed	Ration of alcohol to oil	Reaction time	Settling time	Yields (%)	Reference
H_2SO_4	0.65% (v/v oil)	Methanol	55 °C	350 rpm	7.5:1	4 h	2 h	85	[39]
KOH	0.9% (w/v oil)		66 °C	500 rpm	11.5:1	4 h	13 h		
H_2SO_4	0.65% (v/v oil)	Methanol	–	–	6:1	4 h	–	85	[37]
KOH	1.5% (w/w oil)		–	–	9:1	4 h	–		
H_2SO_4	1% (v/v oil)	Methanol	60 °C	400 rpm	50% (v/v oil)	3 h	–	> 90	[13,53]
KOH	1% (m/m oil)		60 °C	400 rpm	25% (v/v oil)	2 h	24 h		
H_2SO_4	0.75% (v/v oil)	Methanol	60 °C	–	65% (v/v oil)	1 h	90 min	92.5	[40]
KOH	1.0% (w/v)		60 °C		20% (v/v oil)	30 min	1 h		
H_2SO_4	1.5% (v/v oil)	Methanol	60 °C	1000 rpm	12:1	3 h	1 h	> 90	[66]
KOH	1.0% (w/w oil)		60 °C	1200 rpm	20% (v/v oil)	2 h	12 h		

Table 7
Physicochemical properties of *Calophyllum inophyllum* methyl ester (CIME).

Property	Unit	CIMEa	CIME[b]	CIME[c]	CIME[d]	CIME[e]	ASTM D6751	Method
ASTM properties								
Density at 40 °C	kg/m^3	877.6	880.6	–	–	868.6	860–900	ASTM D1298
Kinematic viscosity at 40 °C	mm^2/s (cSt)	5.5377	5.724	4	4.92	4.7128	1.9–6.0	ASTM D445
Oxidation stability	h at 110 °C	6.12	–	–	–	6.01	Min. 3h	ASTM D675
Cloud point	°C	12	–	13.2	13.2	10	Max. 18	ASTM D 2500
Pour point	°C	13	–	–	4.3	8	–	ASTM D 97
CFPP	°C	11	–	–	–	8	Max. 19	ASTM D 6371
Flash point	ºC	162.5	151	140	140	141.5	130 Min	ASTM D93
Copper strip corrosion (50 ºC; 3 h)	–	1a	1b	–	–	–	Max. no.3	ASTM D130
Calorific value	kJ/kg	39,513	–	–	38,660	39,389	N/A	N/A
Sulfur	ppm	4.11	–	–	–	–	500 Max (S500) 15 Max (S15)	ASTM D5453
Non-ASTM properties								
Kinematic viscosity at 100 °C	mm^2/s (cSt)	1.998	–	–	–	–	–	–
Viscosity index	–	183.2	–	–	–	174.7	–	–
Absorbance at WL 656.1	abs	0.057	–	–	–	–	–	–
Transmission at WL 656.1	(%)	87.7	–	–	–	–	–	–
Refractive index at 25 °C	(RI)	1.4574	–	–	–	–	–	–

[a] Reported by [13].
[b] Reported by [38].
[c] Reported by [30].
[d] Reported by [37].
[e] Reported by [66].

the CFPP of CIME was 11 °C [13] compared to 8 °C of [66]. This result is in agreement with ASTM D6371, which requires that CFPP to be maximum 19 °C.

8.4. Cloud point (CP) and pour point (PP)

The behavior of biodiesel at low temperature is an important quality criterion. The cloud point is the temperature at which wax crystals first become visible when the fuel is cooled. Pour point is the temperature at which the amount of wax out of solution is sufficient to gel the fuel, thus it is the lowest temperature at which the fuel can flow. Cloud and pour points are measured using ASTM D2500 and D97 procedures.

It was found that the cloud point of CIME was 12 °C [13], 13.2 °C [37], 13.2 °C [30] and 10 °C [66]. These results are in agreement with ASTM D2500 which requires that the cloud point to be maximum 18 °C. However, the pour point of CIME was 13 °C of [13] higher compared to 4.3 °C [37] and 8 °C [66] as can be seen in Table 7.

8.5. Oxidation stability

The oxidation of biodiesel fuel is one of the major factors that help assess the quality of biodiesel. Oxidation stability is an indication of the degree of oxidation, potential reactivity with air, and can determine the need for antioxidants. The Rancimat method is known as the oxidative stability specification in ASTM D675 with a minimum IP (110 °C) of 3 h. According to [13], it was that the oxidation stability of CIME is 6.18 h. This result agrees with ASTM D675 specification of 3 h minimum for oxidation stability. The result is also comparable with that of [66] of 6.01 h.

8.6. High calorific value

Calorific value is an important parameter in the selection of a fuel. The caloric value of biodiesel is lower than that of diesel because of its higher oxygen content. It can be seen that the obtained result for CIME was 39,474 kJ/kg [13], compared to 38,660 kJ/kg of [37] and 39,389 kJ/kg of [66] (Table 7).

9. Effect of blending

9.1. Biodiesel–biodiesel blending

Atabani et al. [13] discussed the concept of biodiesel–biodiesel blending to improve the properties of the final product. The measured CP, PP and CFPP of *Calophyllum inophyllum* methyl ester were found 12 °C, 13 °C and 11 °C respectively. Therefore, blending of CIME with other biodiesel feedstocks which have good cold flow properties can improve these properties. Fig. 6 shows that blending of Canola methyl ester (CME) and *Calophyllum inophyllum*

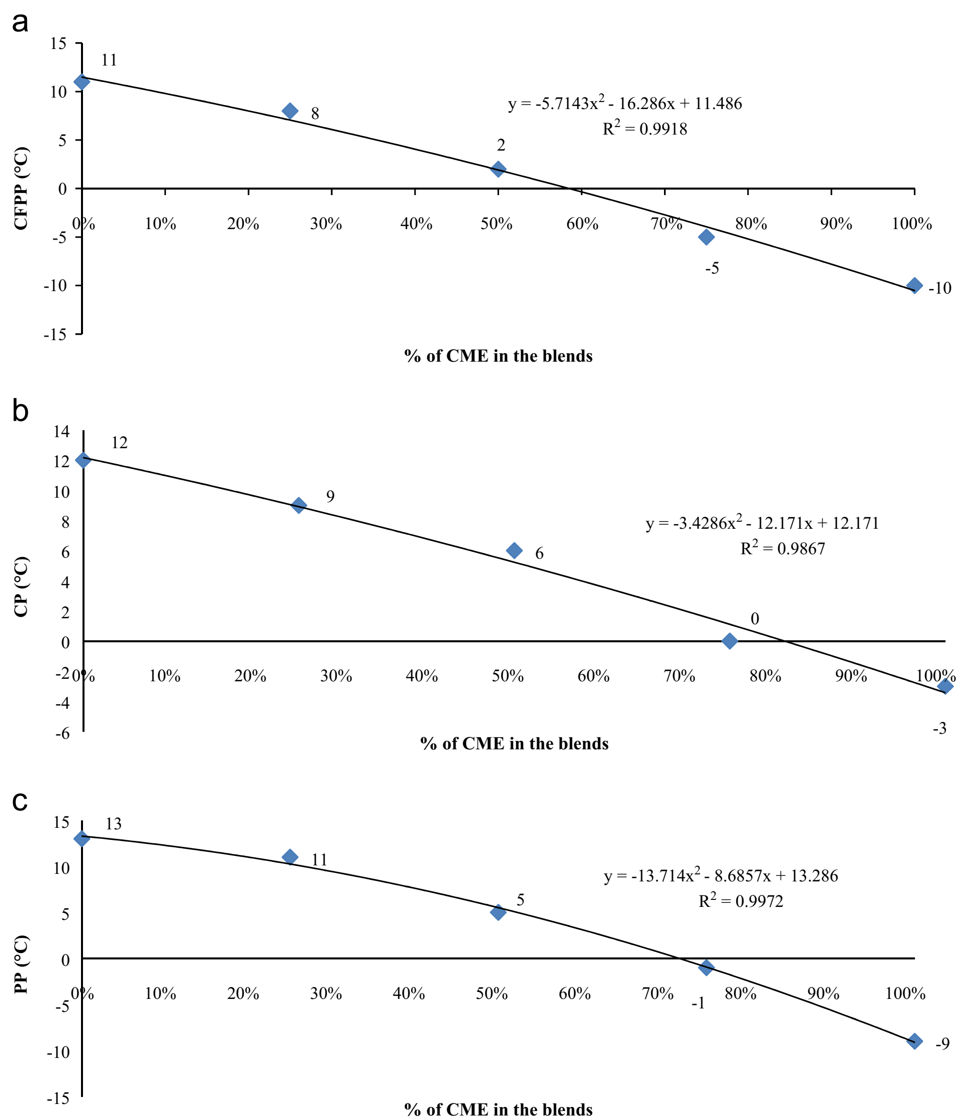

Fig. 6. Effect of blending Canola methyl ester and *Calophyllum inophyllum* methyl ester on CP, PP and CFPP.

methyl ester (CIME) improved remarkably the cold flow properties of CIME.

For instance, a blending ratio of 50% by volume improved the CP of *Calophyllum inophyllum* methyl ester from 12 °C to 6 °C. Moreover, the developed equation from these figures can be used to predict the CFPP, CP and PP of the blend at any blending ratio based on CME% in the blends as follows:

$$CP = -3.4286x^2 - 12.171x + 12.1710 \le x \ge 100R^2 = 0.9867 \quad (1)$$

$$PP = -13.714x^2 - 8.6857x + 13.2860 \le x \ge 100R^2 = 0.9972 \quad (2)$$

$$CFPP = -5.7143x^2 - 16.286x + 11.4860 \le x \ge 100R^2 = 0.9918 \quad (3)$$

9.2. Biodiesel–diesel blending

Sahoo et al. [23,24,37], Atabani [53] and Rizwanul Fattah et al. [66] studied the Physico-chemical properties of neat petro-diesel and *Calophyllum inophyllum* methyl ester (B100) and blends.

Tables 8 and 9 show the fuel properties of *Calophyllum inophyllum* methyl ester in comparison with diesel and blends. It can be seen that oxidation stability improved remarkably when blending with diesel. Calorific value increased with increasing percentage of diesel. Kinematic viscosity and density also decreased with the increasing percentage of diesel.

9.3. Crude oil–diesel blending

Belagur and Chitimi [63] characterized few properties of honne (*Calophyllum inophyllum*) oil and diesel fuel blends. Several properties such as cloud point, pour point, kinematic viscosity (40–100 °C), density, flash point, heating value, carbon residue, ash content and percent of distillate collect were reported in this study. It was found that the important properties of H10–H50 at 60 °C are within the limit set by ASTM standards. Therefore, the author concluded that the H10–H50 at 60 °C can be used directly in diesel engine for short term applications.

10. Engine performance, emissions production and combustion analysis

Sahoo et al. [24] presented the results of engine performance fueled with *Jatropha*, Karanja (*Pongamia pinnata* L.), Polanga (*Calophyllum inophyllum* L.) biodiesel. They observed that the maximum increase in power was observed for 50% Jatropha

Table 8
Properties of *Calophyllum inophyllum* methyl ester (CIME) in comparison with diesel and blends [37].

Fuel blends	Viscosity (cSt)	Calorific value (MJ/kg)	Flash point (°C)	Cloud point (°C)	Pour point (°C)
HSD	2.87	44.22	76	6.5	−3
B20	2.98	43.85	86	7.8	2.8
B40	3.30	42.65	91	8.5	2.8
B60	3.61	40.98	96	10.6	3.2
B80	3.72	39.23	111	10.8	3.6
B100	4.92	38.66	140	13.2	4.3

biodiesel and diesel blend at rated speed while the best brake specific energy consumption (BSEC) improvement was observed with 20% of Polanga biodiesel (PB). Smoke emission reduced with blends and speeds during a full throttle performance test. During part throttle test mode, it was observed that blends with higher percentage of biodiesel tend to decrease the exhaust smoke substantially. A noticeable reduction in HC (4.3–32.28%) and PM (9.88–45.48) was seen with biodiesel and their blends. However, there was a slight increase in CO (5.57–35.21%) and NO_x (4.15–22.5%).

Sahoo et al. [37] tested *Calophyllum inophyllum* methyl ester with high speed diesel (HSD) in a single cylinder diesel engine. In this study, HSD and *Calophyllum inophyllum* methyl ester fuel blends (20%, 40%, 60%, 80%, and 100%) were used for conducting the short-term engine performance tests at varying loads (0%, 20%, 40%, 60%, 80%, and 100%). The main findings of the study showed that the performance of biodiesel-fueled engine was marginally better than the diesel-fueled engine in terms of thermal efficiency, brake specific energy consumption, smoke opacity, and exhaust emissions including NO_x emission for the entire range of operations. The 100% biodiesel was found to be the best, which improved the thermal efficiency of the engine by 0.1%. A similar trend was shown by the brake specific energy consumption and the exhaust emissions were reduced. Smoke emissions also reduced by 35% for B_{60} as compared to neat petro-diesel. Decrease in the exhaust temperature of a biodiesel-fueled engine led to approximately 4% decrease in NO_x emissions for B_{100} biodiesel at full load. It was conclusively proved that excess oxygen content of biodiesel played a key role in engine performance. The authors concluded that *Calophyllum inophyllum* methyl ester can be adopted as an alternative fuel for the existing conventional diesel engines without any major hardware modifications in the system. However, long term endurance test and other tribological studies need to be carried out before suggesting long term application of *Calophyllum inophyllum* methyl ester.

Sahoo and Das [23] studied the combustion of diesel; neat biodiesel from Jatropha, Karanja and *Calophyllum inophyllum*; and their blends (20 and 50 by v%) were used for conducting combustion tests at varying loads (0, 50% and 100%). The engine combustion parameters such as peak pressure, time of occurrence of peak pressure, heat release rate and ignition delay were measured.

The results revealed that the peak pressure for JB100, JB50, JB20, KB100, KB50, KB20, PB100, PB50 and PB20 was 6 bar, 4.09 bar, 2 bar, 5.5 bar, 4.6 bar, 1.7 bar, 6.61 bar, 5.4 bar and 2.2 bar higher than that of diesel, respectively. Therefore, *Calophyllum inophyllum* biodiesel had 8.5% higher peak pressure than that of neat diesel followed by *Jatropha* biodiesel (7.6%) and Karanja biodiesel (6.9%). It was observed that the maximum heat release rate of biodiesel and their blends was lower than that of diesel, specifically, 69.97 J/deg CA for *Jatropha* biodiesel, 70.93 J/deg CA for Karanja biodiesel and 68.37 J/deg CA for *Calophyllum inophyllum* biodiesel compared with 90.96 J/deg CA for diesel. The ignition delays were consistently shorter for neat Jatropha biodiesel, varying between 5.9° and 4.2° crank angles lower than diesel with the difference increasing with the load. Similarly, ignition delays were shorter for neat Karanja biodiesel (varying between 6.3° and 4.5° crank angle) and neat *Calophyllum inophyllum* biodiesel (varying between 5.7° and 4.2° crank angle) lower than diesel.

The authors concluded that further research and development on the additional fuel property measures, long-term run and wear analysis of biodiesel fueled engine is necessary along with injection timing and duration for better combustion of biodiesel in diesel engines.

Rizwanul Fattah et al. [66] investigated the performance and emission study using 10% and 20% blends of Alexandrian laurel (*Calophyllum inophyllum*) in a 55 kW, 2.5 L, four-cylinder indirect injection diesel engine under conditions of constant load and varying speeds. The main findings showed that the brake powers of B10 and B20 reduced 0.36–0.76% compared to diesel. While brake specific fuel consumption (BSFC) increased 2.42–3.20%. The exhaust emissions of HC (9.26–17.04%), CO (15.12–26.84%) and smoke were much better compared to diesel except NO_x emission. NO_x emission increased by 2.12–8.32% compared to diesel.

Atabani [67] evaluated the engine performance and emissions of *Calophyllum inophyllum*, *Croton megalocarpus* and Coconut methyl esters together with their 10% and 20% by volume blends (B_{10} and B_{20}) in a multi-cylinder Mitsubishi Pajero diesel engine. Based on the experimental study, the following conclusions were drawn:

- Over the entire range of speed, the average brake power for $CMME_{10}$, $CMME_{20}$, $CIME_{10}$, $CIME_{20}$, $COME_{10}$, $COME_{20}$ and diesel was 3.94%, 5.95%, 5.06%, 6.85%, 2.43% and 4.88% lower than diesel.
- $CMME_{10}$, $CMME_{20}$, $CIME_{10}$, $CIME_{20}$, $COME_{10}$, $COME_{20}$ gave an average reduction in torque of 4.05%, 5.95%, 5.04%, 6.77%, 2.70% and 4.84% respectively compared to that of diesel.
- $CMME_{10}$, $CMME_{20}$, $CIME_{10}$, $CIME_{20}$, $COME_{10}$, $COME_{20}$ increased the BSFC by 5.3%, 8.9%, 6.85%, 12.33%, 2.99% and 8.31% than diesel fuel.
- Over the entire range of speeds, $CMME_{10}$, $CMME_{20}$, $CIME_{10}$, $CIME_{20}$, $COME_{10}$ and $COME_{20}$ gave an average reduction of CO emission by 8.89%, 29.04%, 16.81%, 34.49%, 15.44% and 34.72% than diesel.
- The average reductions in HC emission for $CMME_{10}$, $CMME_{20}$, $CIME_{10}$, $CIME_{20}$, $COME_{10}$ and $COME_{20}$ compared to diesel were 3.89%, 11.68%, 5.19%, 19.48%, 3.89% and 15.58% respectively.
- The average increase in NO emission for $CMME_{10}$, $CMME_{20}$, $COME_{10}$ and $COME_{20}$ compared to diesel were 7.31%, 8.06%, 1.55% and 6.16% respectively. While the average NO emissions for $CIME_{10}$ and $CIME_{20}$ were 0.54% and 1.49% lower than diesel.

Finally, it can be concluded that CMME, CIME and COME and their B_{10} and B_{20} blends can be used as a diesel fuel substitute with no modifications.

More work on engine performance and emissions from *Calophyllum inophyllum* methyl ester and its blends with diesel can be found in Ref. [46].

11. Effect of adding antioxidants on oxidation stability and engine performance of *Calophyllum inophyllum* methyl ester

Rizwanul Fattah et al. [68] studied the antioxidant addition effect on engine performance and emission characteristics of *Calophyllum inophyllum* blend with diesel (CIB20). In their study, Two monophenolic, 2(3)-tert-Butyl-4-methoxyphenol (BHA) and 2,6-di-tert-butyl-4-methylphenol (BHT) and one diphenolic,

Table 9
Physico-chemical properties of *Calophyllum inophyllum* methyl ester (CIME) and its blends with diesel [53].

		B_0	B_{10}	B_{20}	B_{30}	B_{40}	B_{50}	B_{60}	B_{70}	B_{80}	B_{90}	B_{100}
1	Dynamic viscosity at 40 °C	2.6996	2.8575	3.0447	3.2184	3.4505	3.6664	3.9061	4.1748	4.4541	4.7746	5.0446
2	Kinematic viscosity at 40 °C	3.2333	3.4066	3.6105	3.7995	4.0512	4.2841	4.5419	4.829	5.1263	5.4657	5.7499
3	Kinematic viscosity at 100 °C	1.2446	1.315	1.3931	1.4552	1.5344	1.6081	1.6916	1.7643	1.8586	1.9527	2.0344
4	Density at 40 °C	0.8349	0.8388	0.8433	0.8471	0.8517	0.8558	0.86	0.8645	0.8689	0.8736	0.8774
5	Viscosity index	90	122.5	130.8	139.2	149.7	156.4	159.6	161.6	163.5	168.9	174.9
6	Cloud point (CP)	8	8	8	7	7	7	7	7	8	9	10
7	Pour point (PP)	0	1	1	4	4	6	6	6	8	8	11
8	Cold filter plugging point (CFPP)	5	7	6	5	4	4	2	2	4	7	9
9	Oxidation stability	N/D	47.75	23.61	14.38	9.67	N/D	5.67	N/D	3.95	N/D	0.09
10	Calorific value	45,304	44,578	44,065	43,278	42,471	41,787	41,212	40,900	40,337	39,561	39,273
11	Flash point	68.5	72.5	73.5	N/D	75.5	N/D	81.5	N/D	87.5	N/D	93.5

2-tert-butylbenzene-1,4-diol (TBHQ) were added at 2000 ppm concentration to 20% CIBD (CIB20).

It was found that TBHQ in general produces the best stabilization to pure CIBD as well as CIB20. Moreover, the addition of antioxidant increased kinematic viscosity, density, flash point as well as oxidation stability but reduced the calorific value.

The results of engine performance indicated that CIB20 produced 1.42% lower mean brake power (BP), 4.90% higher mean brake specific fuel consumption (BSFC) and 2.83% higher mean brake specific energy consumption (BSEC) compared to diesel. However, the addition of antioxidants increased BP (0.42–0.83%) and reduced BSFC (0.5–1.5%) and BSEC (0.78–1.92%).

Emission results showed that CIB20 increased NO_x (5.5%) but decreased CO (39.14%) and HC (26.5%) emission. Antioxidants reduced 1.6–3.6% NO_x emission, but increased both CO (5.76–14.71%) and HC (9.9–21.6%) emission compared to CIB20. However, the level was below the diesel emission level. The authors concluded that CIB20 blends with antioxidants can be used in diesel engines without any modification.

12. Conclusion and recommendations

The main objective of the present paper is to investigate the potential of *Calophyllum inophyllum* as a promising feedstock for biodiesel production. In this paper, several aspects such as physical and chemical properties of crude *Calophyllum inophyllum* oil (CCIO) and methyl ester (CIME), fatty acid composition (FAC), biodiesel–diesel blending, biodiesel–biodiesel blending, crude oil–diesel blending, effect of adding antioxidants and engine performance and emissions of *Calophyllum inophyllum* methyl ester were studied.

Crude *Calophyllum inophyllum* oil was reported to be highly acidic. Therefore, a two-step of acid–base catalyzed transesterification process was used to produce biodiesel from this feedstock. The results of fatty acid composition showed that (CCIO) is mainly dominated by C18:1 followed by C18:2, C18:0 and C16:0 acids.

The fuel properties of *Calophyllum inophyllum* methyl ester (CIME) were compared with literature and ASTM D6751 biodiesel standards. Blending of CIME with diesel and other biodiesel feedstocks resulted in a remarkable improvement in some physical and chemical properties. For instance, blending Canola methyl ester (CME) and *Calophyllum inophyllum* methyl ester (CIME) improved remarkably the cold flow properties of CIME such as cloud, pour and cold filter plugging point.

The summary of engine performance and emission results of *Calophyllum inophyllum* methyl ester (CIME) showed different trends. Some studies reported that higher percentage of biodiesel tend to decrease brake power, torque, CO and HC and increase BSFC and NO_x.

While some others reported that the blends with higher percentage of biodiesel tend to decrease HC and PM and increase CO and NO_x. Some authors reported that the performance of biodiesel-fueled engine was marginally better than the diesel-fueled engine in terms of thermal efficiency, brake specific energy consumption, smoke opacity, and exhaust emissions including NO_x emission for entire range of operations.

As a conclusion, *Calophyllum inophyllum* seems to be a satisfactory feedstock for future biodiesel production. Therefore, further studies on improvement of physical and chemical properties as well as engine performance, combustion and emissions tests should be conducted.

References

[1] Ahmad AL, Mat Yasin NH, Derek CJC, Lim JK. Microalgae as a sustainable energy source for biodiesel production: a review. Renew Sustain Energy Rev 2011;15(1):584–93.
[2] Venkanna BK, Reddy CV. Biodiesel production and optimization from *Calophyllum inophyllum* linn oil (honne oil) – a three stage method. Bioresour Technol 2009;100(21):5122–5.
[3] Canakci M, Sanli H. Biodiesel production from various feedstocks and their effects on the fuel properties. J Ind Microbiol Biotechnol 2008;35:431–41.
[4] Moser MR. Biodiesel production, properties, and feedstocks. in vitro Cell Dev. Biol. Plant 2009:229–6645 2009:229–66.
[5] Kafuku G, Mbarawa M. Biodiesel production from *Croton megalocarpus* oil and its process optimization. Fuel 2010;89(9):2556–60.
[6] Rashid U, Anwar F, Moser BR, Knothe G. *Moringa oleifera* oil: a possible source of biodiesel. Bioresour Technol 2008;99(17):8175–9.
[7] Janaun J, Ellis N. Perspectives on biodiesel as a sustainable fuel. Renew Sustain Energy Rev 2010;14(4):1312–20.
[8] Atadashi IM, Aroua MK, Abdul Aziz A. High quality biodiesel and its diesel engine application: a review. Renew Sustain Energy Rev 2010;14(7):1999–2008.
[9] Karmakar A, Karmakar S, Mukherjee S. Properties of various plants and animals feedstocks for biodiesel production. Bioresour Technol 2010;101 (19):7201–10.
[10] Atabani AE, Silitonga AS, Badruddin Irfan Anjum, Mahlia TMI, Masjuki HH, Mekhilef S. A comprehensive review on biodiesel as an alternative energy resource and its characteristics. Renew Sustain Energy Rev 2012;16(4):2070–93.
[11] Lim S, Teong LK. Recent trends, opportunities and challenges of biodiesel in Malaysia: an overview. Renew Sustain Energy Rev 2010;14(3):938–54.
[12] Lin L, Cunshan Z, Vittayapadung S, Xiangqian S, Mingdong D. Opportunities and challenges for biodiesel fuel applied energy 2011;88(4):1020–31.
[13] Atabani AE, Mahlia TMI, Masjuki HH, Badruddin Irfan Anjum, Yussof Hafizuddin Wan, Chong WT, et al. A comparative evaluation of physical and chemical properties of biodiesel synthesized from edible and non-edible oils and study on the effect of biodiesel blending. Energy 2013;58:296–304.
[14] Balat M, Balat H. Progress in biodiesel processing. Appl Energy 2010;87 (6):1815–35.
[15] Balat M. Potential alternatives to edible oils for biodiesel production – a review of current work. Energy Convers Manag 2011;52(2):1479–92.
[16] Gui MM, Lee KT, Bhatia S. Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock. Energy 2008;33(11):1646–53.
[17] Mohibbe Azam M, Waris A, Nahar NM. Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India. Biomass Bioenergy 2005;29(4):293–302.
[18] Berchmans HJ, Hirata S. Biodiesel production from crude *Jatropha curcas* L. seed oil with a high content of free fatty acids. Bioresour Technol 2008;99 (6):1716–21.
[19] Chhetri AB, Tango MS, Budge SM, Watts KC, Rafiqul Islam M. Non-edible plant oils as new sources for biodiesel production. Int J Mol Sci 2008;9(2):169–80.

[20] Sharma YC, Singh B, Upadhyay SN. Advancements in development and characterization of biodiesel: a review. Fuel 2008;87(12):2355–73.
[21] Syers KJ, Wood D, Thongbai P. Feasibility of non-edible oil seed crops for biofuel production. in international technical workshop; 2008. Chiang Rai, Thailand: School of Science, Mae Fah Luang University, Thailand. Center for Academic Services, Mae Fah Luang University, Thailand. Institute for Research on Environment and Sustainability, Newcastle University, United Kingdom.
[22] Razon LF. Alternative crops for biodiesel feedstock. CAB Rev: Persp Agric, Vet Sci, Nutr Nat Resour 2009;4(56):1–15.
[23] Sahoo PK, Das LM. Combustion analysis of jatropha, karanja and polanga based biodiesel as fuel in a diesel engine. Fuel 2009;88(6):994–9.
[24] Sahoo PK, Das LM, Babu MKG, Arora P, Singh VP, Kumar NR, et al. Comparative evaluation of performance and emission characteristics of jatropha, karanja and polanga based biodiesel as fuel in a tractor engine. Fuel 2009;88 (9):1698–707.
[25] Pinzi S, Garcia IL, Lopez-Gimenez FJ, Luque de Castro MD, Dorado G, Dorado MP. The ideal vegetable oil-based biodiesel composition: a review of social, economical and technical implications. Energy Fuels 2009;23(5):2325–41.
[26] Kansedo J, Lee KT, Bhatia S. *Cerbera odollam* (sea mango) oil as a promising non-edible feedstock for biodiesel production. Fuel 2009;88(6):1148–50.
[27] da Silva JPV, Serra TM, Gossmann M, Wolf CR, Meneghetti MR, Meneghetti SMP. *Moringa oleifera* oil: studies of characterization and biodiesel production. Biomass Bioenergy 2010;34(10):1527–30.
[28] Jena PC, Raheman H, Kumar GVP, Machavaram R. Biodiesel production from mixture of mahua and simarouba oils with high free fatty acids. Biomass Bioenergy 2010;34(8):1108–16.
[29] Kumar A, Sharma S. Potential non-edible oil resources as biodiesel feedstock: an Indian perspective. Renew Sustain Energy Rev 2011;15(4):1791–800.
[30] SathyaSelvabala V, Selvaraj DK, Kalimuthu J, Periyaraman PM, Subramanian S. Two-step biodiesel production from *Calophyllum inophyllum* oil: optimization of modified b-zeolite catalyzed pre-treatment. Bioresour Technol 2011;102 (2):1066–72.
[31] Silitonga AS, Atabani AE, Mahlia TMI, Masjuki HH, Badruddin Irfan Anjum, Mekhilef S. A review on prospect of *Jatropha curcas* for biodiesel in Indonesia. Renew Sustain Energy Rev 2011;15(8):3733–56.
[32] Wang R, Hanna MA, Zhou W, Bhadury PS, Chen Q, Song B, et al. Production and selected fuel properties of biodiesel from promising non-edible oils: *Euphorbia lathyris* L., *Sapium sebiferum* L. and *Jatropha curcas* L. Bioresour Technol 2011;102(2):1194–9.
[33] Deka DC, Basumatary S. High quality biodiesel from yellow oleander (*Thevetia peruviana*) seed oil. Biomass Bioenergy 2011;35(5):1797–803.
[34] Rashid U, Anwar F, Knothe G. Biodiesel from Milo (*Thespesia populnea* L.) seed oil. Biomass Bioenergy 2011;35(9):4034–9.
[35] Murugesan A, Umarani C, Chinnusamy TR, Krishnan M, Subramanian R, Neduzchezhain N. Production and analysis of bio-diesel from non-edible oils – a review. Renew Sustain Energy Rev 2009;13(4):825–34.
[36] Bankovic-Ilic IB, Stamenkovic OS, Veljkovic VB. Biodiesel production from non-edible plant oils. Renew Sustain Energy Rev 2012;16(6):3621–47.
[37] Sahoo PK, Das LM, Babu MKG, Naik SN. Biodiesel development from high acid value polanga seed oil and performance evaluation in a CI engine. Fuel 2007;86(3):448–54.
[38] Sudradjat R. *Calophyllum inophyllum* L. –a potential plant for biodiesel; 2011 [cited 2012 19th November]; Available from: 〈http://www.iges.or.jp/en/bf/pdf/activity20090204/session2/Sudradjat.pdf〉.
[39] Sahoo PK, Das LM. Process optimization for biodiesel production from jatropha, karanja and polanga oils. Fuel 2009;88(9):1588–94.
[40] Ramaraju A, Ashok Kumar TV. Biodiesel development from high free fatty acid punnakka oil. ARPN J Eng Appl Sci 2011;6(4):1–6.
[41] Ministry of Forestry of the Republic of Indonesia (The Forestry Research and Development Agency). Nyamplung *Calophyllum inophyllum* L sumber energi biofuel yang potensial 2008, Jakarta, Indonesia: Forestry information centre.
[42] Dweck C, Meadows T. Tamanu (*Calophyllum inophyllum*) – the African, Asian, Polynesian and Pacific Panacea. Int J Cosmet Sci 2002;24(6):341–8.
[43] Crane S, Aurore G, Joseph H, Mouloungui Z, Bourgeois P. Composition of fatty acids triacylglycerols and unsaponifiable matter in *Calophyllum calaba* L. oil from Guadeloupe. Phytochemistry 2005;66(15):1825–31.
[44] Atabani AE, Badruddin Irfan Anjum, Mahlia TMI, Masjuki HH, Chong WT, Keat Teong Lee. Investigation of physical and chemical properties of potential edible and non-edible feedstcoks for biodiesel production, a comparative analysis. Renew Sustain Energy Rev 2013;21:749–55.
[45] Friday JB, Okano D. *Calophyllum inophyllum* (kamani); 2012 [cited 05.04.13]. Available from: http://www.agroforestry.net/tti/Calophyllum-kamani.pdf.
[46] Sanjid A, Masjuki HH, Kalam MA, Ashrafur Rahman SM, Abedin MJ, Palash SM. Impact of palm, mustard, waste cooking oil and *Calophyllum inophyllum* biofuels on performance and emission of CI engine. Renew Sustain Energy Rev 2013;27:664–82.
[47] Worldagroforestry. *Calophyllum inophyllum*. Available from: http://www.worldagroforestry.org/treedb2/AFTPDFS/Calophyllum_inophyllum.pdf; 2011 [cited 18.04.12].
[48] Bora DK, Das LM, Babu MKG. Performance of mixed biodiesel fueled diesel engine. J Sci Ind Res India 2008;67:73–6.
[49] Mohod AG, Bhor PP, Kadam KN, Sengar SH, Khandetod YP. Study of properties of *Calophyllum inophyllum* L. oil and its biodiesel. Int J Agric Eng (IJAE) 2010;3 (1):125–9.
[50] Hathurusingha S, Ashwath N, Midmore D. Provenance variations in seed-related characters and oil content of *Calophyllum inophyllum* L. in northern Australia and Sri Lanka. New Forests 2011;41(1):89–94.
[51] Hathurusingha S, Ashwath N, Midmore D. Periodic variation in kernel oil content and fatty acid profiles of *Calophyllum innophyllm* L.: a potential biodiesel feedstock in Australia. Biomass Bioenergy 2011;35(8):3448–52.
[52] Atabani AE, Silitonga AS, Ong HC, Mahlia TMI, Masjuki HH, Badruddina Irfan Anjum, et al. Non-edible vegetable oils: a critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. Renew Sustain Energy Rev 2013;18:211–45.
[53] Atabani AE. A comprehensive analysis of edible and non-edible biodiesel feedstocks, in mechanical engineering. Malaysia: University of Malaya: Kuala Lumpur; 2013; 188.
[54] Prakoso T, Soerawidjaja TH., Biofuel Researches at Institute Teknologi Bandung, 2007, Institute Teknologi Bandung: Bandung.
[55] No SY. Inedible vegetable oils and their derivatives for alternative diesel fuels in CI engines: a review. Renew Sustain Energy Rev 2011;15(1):131–49.
[56] Hathurusingha S, Ashwath N, Subedi P. Variation in oil content and fatty acid profile of *Calophyllum inophyllum* L. with fruit maturity and its implications on resultant biodiesel quality. Ind Crops Prod 2011;33(3):629–32.
[57] Lokesh AC, Mahesh NS. Strategies for the sustainability of bio diesel production from feed stock in India: a review. Agric Eng Int: CIGR Ejournal 2011; XI:1–6.
[58] César AS. The competitiveness of the biodiesel production in Brazil: a comparative analysis of castor, palm and soy, in Department of Management Engineering. Brazil: Federal University of São Carlos, São Carlos; 2012 ([in Portuguese]).
[59] Knothe G, Krahl J, Van Gerpen J, Ramos LP. A história dos combustíveis derivados de óleos vegetais. São Paulo, Brazil: Edgard Blücher; 2006 ([in Portuguese]).
[60] Gressel G. Transgenics are imperative for biofuel crops. Plant Sci 2008;174 (3):246–63.
[61] Antizar-Ladislao B, Turrion-Gomez JL. Second-generation biofuels and local bioenergy systems. Biofuels Bioprod Biorefin 2008;2:455–69.
[62] Hathurusingha S. Periodic variation in kernel oil content and fatty acid profiles of *Calophyllum inophyllum* L.: a medicinal plant in northern Australia. Ind Crops Prod 2011;33(3):775–8.
[63] Belagur VK, Chitimi VR. Few physical, chemical and fuel related properties of *Calophyllum inophyllum* linn (honne) oil and its blends with diesel fuel for their use in diesel engine. Fuel 2013;109:356–61.
[64] Tong D, Hu C, Jiang K, Li Y. Cetane number prediction of biodiesel from the composition of the fatty acid methyl esters. J Am Oil Chem Soc 2011;88 (3):415–23.
[65] Azam MM, Waris A, Nahar NM. Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India. Biomass Bioenergy 2005;29(4):293–302.
[66] Rizwanul Fattah IM, Kalam MA, Masjuki HH, Wakil MA., Biodiesel production, characterization, engine performance, and emission characteristics of Malaysian Alexandrian laurel oil. RSC Adv 2014;4:17787–17796.
[67] Atabani AE, Badruddin Irfan Anjum, Mahlia TMI, Masjuki HH, Mofijur M, Lee Keat Teong, et al. Fuel properties of *Croton megalocarpus*, *Calophyllum inophyllum*, and *Cocos nucifera* (coconut) methyl esters and their performance in a multicylinder diesel engine. Energy Technol 2013;1:685–94.
[68] Rizwanul Fattah IM, Masjuki HH, Kalam MA, Wakil MA, Ashraful AM, Shahir SA. Experimental investigation of performance and regulated emissions of a diesel engine with *Calophyllum inophyllum* biodiesel blends accompanied by oxidation inhibitors. Energy Convers Manag 2014;83:232–40.